UTILITIES AND RENEWABLE ENERGY

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The Looming Crisis in Generation Capacity

In this research report, we estimate the cumulative loss of dispatchable generation capacity in the United States over the next two decades due to the retirement of aging fossil and nuclear power plants. Our forecast of these retirements allows us to calculate the future erosion of the country's 945 GW of dispatchable generation capacity and compare the remaining capacity to historical peaks in U.S. power demand. We estimate that 32% of the country's dispatchable generation capacity will be retired by 2030, 63% by 2035, and 72% by 2040. (See ***Exhibit 1****.)*

Our analysis assumes that currently operating power plants whose retirement has been announced will be retired on schedule. Where retirements have not been announced, we assume that currently operating generating units will be retired when they reach the age at which plants with similar generating technologies have been retired in the past (30 years for gas-fired combustion turbines and combined cycle power plants, 50 years for fossil fuel steam turbine generators, and 60 years for nuclear plants).

Driving retirements through 2030 will be the advanced age of the country's fossil fuel steam turbine and simple cycle gas turbine power plants. The difference between the capacity weighted average age of these plants and the average age of similar plants at retirement historically is less than 10 years. (See ***Exhibit 2****.) These fossil plants also have high rates of CO2 emissions per MWh, with coal-fired steam turbine plants averaging 1.0 metric ton of CO2 per MWh, oil-fired steam turbines 0.8 Mt CO2/MWh, simple cycle gas turbines 0.6 Mt CO2/MWh and gas-fired steam turbines 0.5 Mt CO2/MWh. (See* ***Exhibit 3****.) Utilities seeking to reduce their carbon emissions have therefore announced the early retirement of many coal and oil-fired units. We expect the bulk of the fossil fuel steam turbine generator fleet, accounting for 305 GW or 32% of U.S. dispatchable generation capacity, to be retired in the current decade. (See* ***Exhibits 4 & 5****.) The fleet of simple cycle gas turbines, totaling 129 GW or 14% of U.S. dispatchable capacity, is also vulnerable to retirements during the current decade, with units commissioned in the 1990s likely to be withdrawn from service. In the 2030s, retirements will largely reflect the loss of simple and combined cycle gas turbine generators commissioned during the boom in gas turbine additions from 1998 through 2025, when over 200 GW of gas turbine capacity was built, as well as rising retirements of nuclear capacity.*

The cumulative impact of these capacity retirements, we calculate, will be to decommission ~300 GW or almost a third of U.S. dispatchable generation capacity by 2030, ~600 GW or 63% of dispatchable capacity by 2035, and ~680 GW or 72% of dispatchable capacity by 2040. Allowing for ongoing additions of dispatchable capacity at the average pre-pandemic pace of 11 GW per year, the scale of these retirements will cause U.S. dispatchable capacity to fall short of the historical peak in power demand by 150 GW by 2032, 250 GW by 2034 and by 300 GW by 2036.[1] *(See* ***Exhibits 7*** *through* ***9****.) Even on the assumption that peak summer demand fails to grow over the over the next decade, the additions of dispatchable generation capacity required to offset this shortfall are equivalent to ~30*

[1] U.S. non-coincident summer demand peaked at 789 GW in 2007 and again in 2012.

GW annually through 2030, nearly triple the average capacity additions of 11 GW annually achieved over the five pre-pandemic years (2015-2019). (See ***Exhibit 13****.)*

Intermittent renewable resources, even when combined with grid scale energy storage, can only offset to a limited degree the loss of firm capacity expected over the next two decades. As explained in our research report of June 18, 2019, The Cost to Achieve 100% Renewable Energy: A Comparative Analysis of Texas and California, the energy output of the lost capacity can be substituted by renewables; however, the load serving capability of the lost resources – their ability to provide power as required to meet demand – can be replaced with a combination of intermittent wind, solar and storage only at prohibitive cost.

The impending loss of 63% of the country's dispatchable generation capacity by 2035 is therefore an issue that must be addressed with the same urgency as the transition to renewable sources of energy. Failure to do so, and the consequent loss of system reliability, will interrupt and potentially derail the transition from fossil fuels to renewable energy in the power sector, as well as the electrification of energy use in transportation, industry, and commercial and residential buildings that could enable their transition from fossil fuels.

The scale and immediacy of the capacity challenge, moreover, should spur serious consideration of alternative strategies to ensure system reliability. In particular, alternatives such as carbon capture and sequestration, the firing of existing gas turbine generators with green hydrogen or green methane, modular nuclear reactors, and long duration energy storage technologies such as pumped hydro storage should be assessed against the prohibitively high marginal cost of substituting firm capacity with intermittent renewable resources backstopped by short duration energy batteries.

Equally important will be the creation of economic incentives to deploy these low-emitting replacements for the nation's fossil fuel generation capacity and maintain large portions of the existing fleet until they can be replaced or retrofitted with these alternatives. Regulated utilities will have to work with their regulators to identify, design and deploy the lowest cost options to maintain system reliability while still achieving emissions reduction targets. Regional transmission organizations operating competitive markets for energy and capacity must redesign these markets to create incentives for a wider range of power generation and CO2 abatement technologies. Importantly, these technologies will often involve larger capital outlays per megawatt, significantly higher technological risk, and longer construction periods than are typical of the gas turbine capacity additions these markets target today.

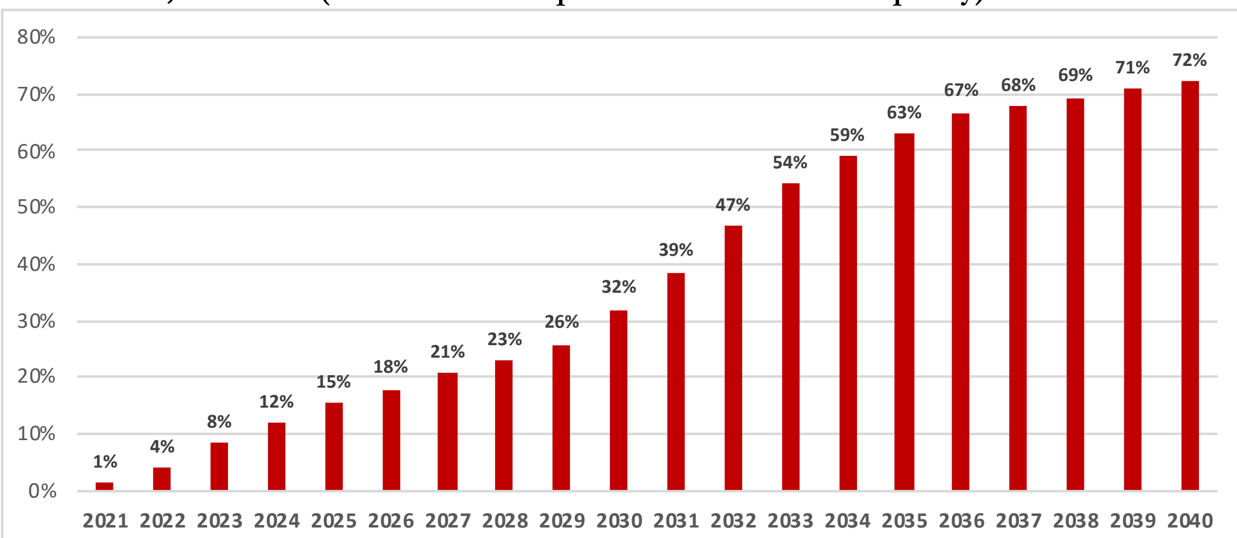
Details

- **State and federal energy policies over the last decade have focused increasingly on the substitution of renewable for fossil energy in the generation of electricity as a means of reducing the sector's CO2 emissions.**
  - Having rejoined the Paris Agreement on climate change, the Biden administration has committed the U.S. to a 50% cut in greenhouse gas emissions from 2005 levels by 2030. In addition, the Biden administration has set a target of eliminating power sector emissions of CO2 by 2035 and achieving zero net emissions of greenhouse gases across the economy by 2050.
  - Sixteen states and territories, with a combined population of 120 million and accounting for 36% of the U.S. population, have legislated renewable portfolio standards requiring utilities to procure between 50% to 100% of the electricity they supply from renewable resources.
  - The policy goals and legislative mandates will make it increasingly difficult for U.S. utilities to continue to operate substantial coal or oil-fired generating fleets.
- **While requiring utilities to increase their reliance on renewable resources, state and federal policies fail to address how utilities are to maintain historical standards of grid reliability as they transition from dispatchable fossil to intermittent renewal sources of energy such as solar and wind.**

- **Recent events, including the deep and prolonged load shedding in Texas during last February's winter storm, and last summer's rolling blackouts in California, the first in 20 years, indicate that the reliability of the bulk power system is eroding long before the transition to renewable energy is complete. Our analysis of these events suggests that that the transition from coal to lower emitting natural gas in power generation, as well as the transition from fossil to renewable energy, have contributed to this erosion.** (See our research report of March 30th*, A Perfect Storm: How Decarbonization, Electrification, Climate Change and Outdated Modeling Are Undermining the Reliability of the Grid* .)
    - In 2000, 99.7% of the electricity on the U.S. power grid was supplied by dispatchable power plants, including coal, gas and oil-fired generating units, nuclear power plants and hydroelectric power stations. Two decades later, this share had fallen to 87%, while intermittent renewable resources such as wind and solar now account for 13% of the nation's generation capacity.
    - Second, in 2000, dispatchable power plants whose energy source was located on site accounted for 72% of the total capacity on the U.S. power grid; two decades later, such power plants account for only 44% of the capacity on the grid. The remainder comprises gas-fired power plants, reliant on the gas transmission system for fuel, and intermittent wind and solar resources.
- **Aggravating the impact of these changes in the composition of power supply are changes in the nature of power demand that have eroded the accuracy of grid planners' assessments of resource adequacy.**
    - There is evidence that extreme weather events have become more frequent, increasing the risk of a severe weather in any particular year.
    - Extreme weather events have also become more geographically widespread, taxing generation resources and fuel supply infrastructure over wider regions and constraining the ability of these regional resources to respond to localized increases in demand.
    - In the southern regions of the country, the growing popularity of air source heat pumps for home heating has increased the sensitivity of power demand to extreme cold, limiting the usefulness of historical relationships between temperature and power demand to forecast load.
    - In the western states, the spread of distributed solar generation has made it more difficult for system operators to monitor gross demand for electricity, aggravating the risk of power supply shortfalls after sunset when the load previously served by rooftop solar returns to the grid.
- **More importantly, these demand and supply risks tend to materialize simultaneously, and can cause cascading failures on the power grid and gas supply infrastructure. Cold winter weather in particular tends to curtail the availability of generating resources even as power demand surges.**
    - During the Texas blackout, every class of generation capacity in the state, including nuclear, coal, gas and wind, was found to be vulnerable to equipment failures caused by extreme cold.
    - Severe winter weather also occurs when the solar resource is at its annual minimum, due to short hours of daylight and a sun that is low in the sky. The coldest winter temperatures tend to occur in the pre-dawn hours when the sun is not shining at all.
    - During extreme cold events, increased demand for heating adds not only to electricity demand but also to the demand for natural gas, reducing pipeline pressure and limiting the ability of gas fired generators to fire up their plants or to operate them at full capacity.
    - Load shedding to avoid a system blackout can in the winter time have the unintended consequence of cutting power supplies to gas production and transmission infrastructure, as occurred during the February load shedding in Texas, further curtailing power supply.
- **Traditional methods of assessing resource adequacy, including the simple comparison of total system capacity to forecast peak demand, fail to reflect adequately the implications of these simultaneous failures, forcing system operators to transition to far more complex probabilistic models to estimate the hourly availability of generation resources in different scenarios.**
- **Over the next several years, system planners will confront a still more serious risk: the rapid loss of dispatchable generation capacity as aging fossil and nuclear power plants reach the end of their useful lives.**

- **Exhibit 1 presents our estimate of the cumulative loss of dispatchable generation capacity to due retirements over the next two decades.**
  - Our analysis assumes that currently operating power plants whose retirement has been announced will be retired on schedule.
  - Where this information is not available, we assume that currently operating generating units will be retired when they reach the age at which plants using similar generating technologies have been retired in the past (30 years for simple and combined cycle gas turbines, 50 years for fossil fuel steam turbine generators, and 60 years for nuclear plants).
- **We find that 32% of the country's 944 GW of dispatchable generation capacity is likely to be retired by 2030, 63% by 2035 and 72% by 2040.**

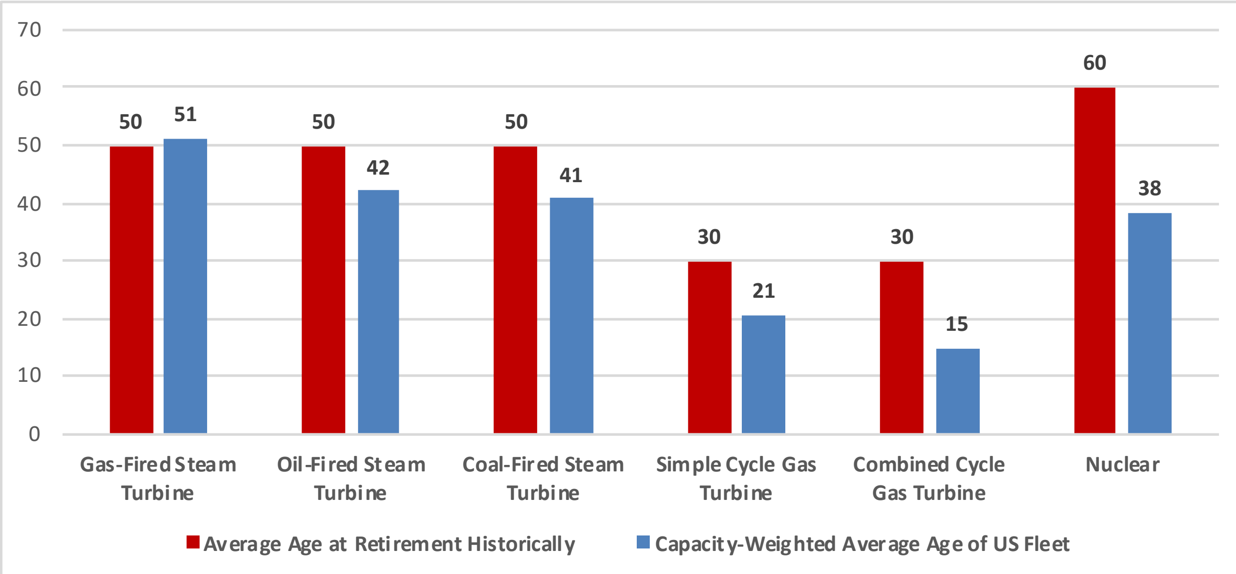
Exhibit 1: Cumulative Loss of Dispatchable Generation Capacity to Retirements, 2021-2040 (As % of 2020 Dispatchable Generation Capacity)



Source: Energy Information Administration (EIA)

- **This rapid pace of capacity retirements reflects the advanced age of the U.S. fossil fuel fleet, and particularly its fossil fuel steam turbine generators and simple cycle gas turbines.**
  - **Exhibit 2** compares (i) the capacity weighted average age of U.S. fossil fuel and nuclear power plants to (ii) the average age at retirement of similar power plants in the past.
  - Based on these averages, **Exhibit 3** estimates the average remaining useful life of each of component of the nation's currently operating dispatchable generation capacity.
  - As can be seen there, the average remaining useful life of the U.S. fossil fuel steam turbine fleet and simple cycle gas turbine fleet is less than 10 years. Together, these power plants account for over half of the currently operating dispatchable capacity in the United States.
  - The last component of the U.S. fossil fuel fleet, the combined cycle gas turbines, has an average remaining useful life of only 15 years.
  - Taken together, these fossil fuel power plants account for over 80% of the nation's currently operating dispatchable generation capacity.

Exhibit 2: Average Age at Retirement, Historically, of Power Plants in the United States Compared to the Capacity Weighted Average Age of Operating U.S. Power Plants



Source: Energy Information Administration (EIA)

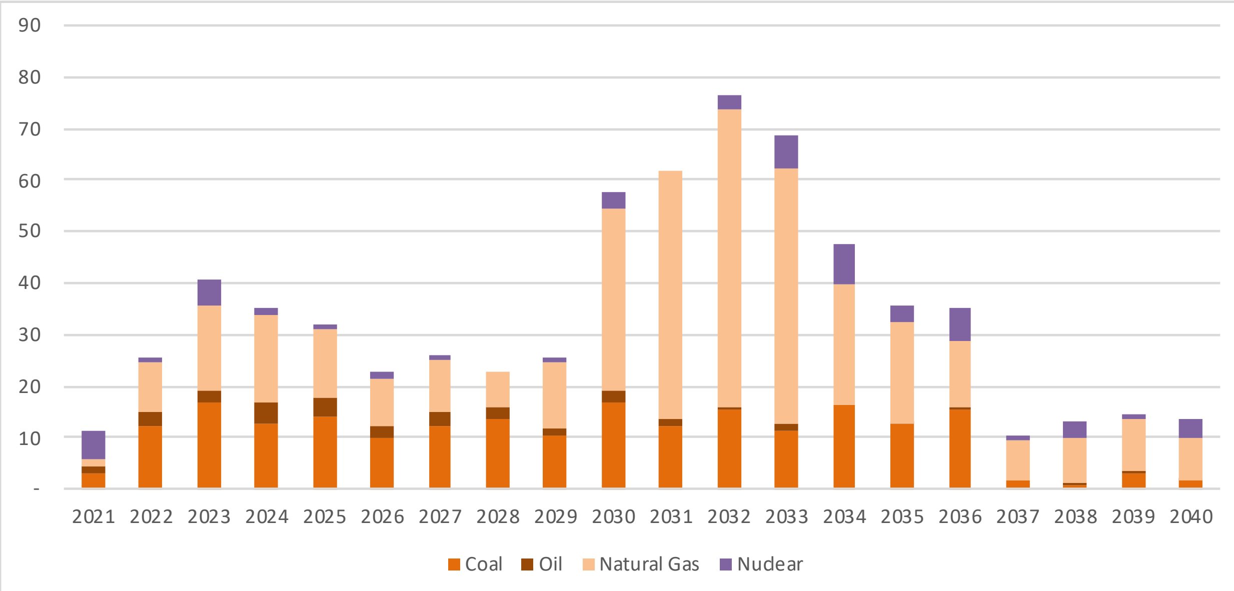
Exhibit 3: Estimated Average Years to Retirement of Power Plants in the United States Compared to Share of U.S. Dispatchable Generation Capacity (Cumulative Percentage)

	Average Remaining Useful Life	Average CO2 Emissions Rate	Capacity in Operation	Share of US Dispatchable Capacity	
	Years	Mt CO2/MWh	GW	By Class of Plant	Cumulative
Gas-Fired Steam Turbine	0	0.5	72	8%	8%
Oil-Fired Steam Turbine	8	0.8	11	1%	9%
Coal-Fired Steam Turbine	9	1.0	223	24%	32%
Simple Cycle Gas Turbine	9	0.6	129	14%	46%
Combined Cycle Gas Turbine	15	0.4	274	29%	75%
Nuclear	22	None	97	10%	85%
Total			806	85%	

Source: Energy Information Administration (EIA)

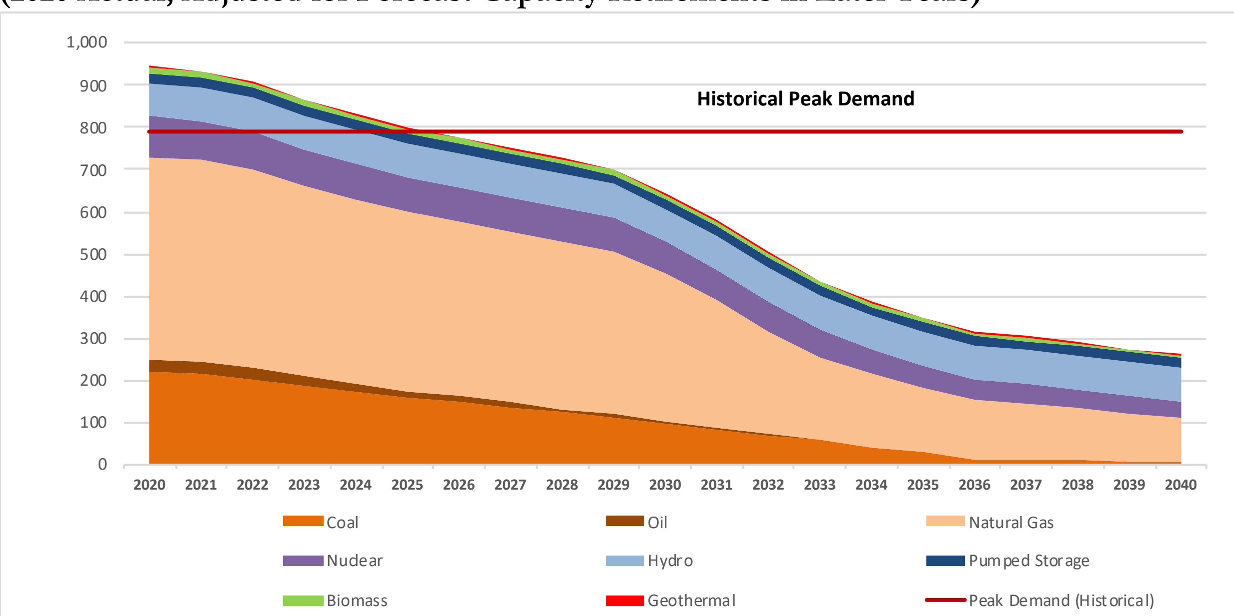
- **These fossil plants also have high rates of CO2 emissions per MWh, with coal-fired plants averaging 1.0 metric ton of CO2 per MWh, oil-fired plants 0.8 Mt CO2/MWh, simple cycle gas-fired plants 0.6 Mt CO2/MWh and gas-fired steam turbines 0.5 Mt CO2/MWh.** (See **Exhibit 3**.)
  - Utilities seeking to reduce their carbon emissions have therefore announced the early retirement of many coal and oil-fired units. We expect the bulk of the fossil fuel steam turbine generator fleet, accounting for 360 GW or 38% of U.S. dispatchable generation capacity, to be retired in the current decade.
  - In the 2030s, retirements will largely reflect the loss of simple and combined cycle gas turbine generators commissioned during the boom in gas turbine additions from 1998 through 2025, when over 200 GW of gas turbine capacity was built, as well as rising retirements of nuclear capacity. (See **Exhibits 4** & **5**.)

Exhibit 4: Estimated Retirements of U.S. Fossil and Nuclear Generation Capacity, 2021-2040 (GW)



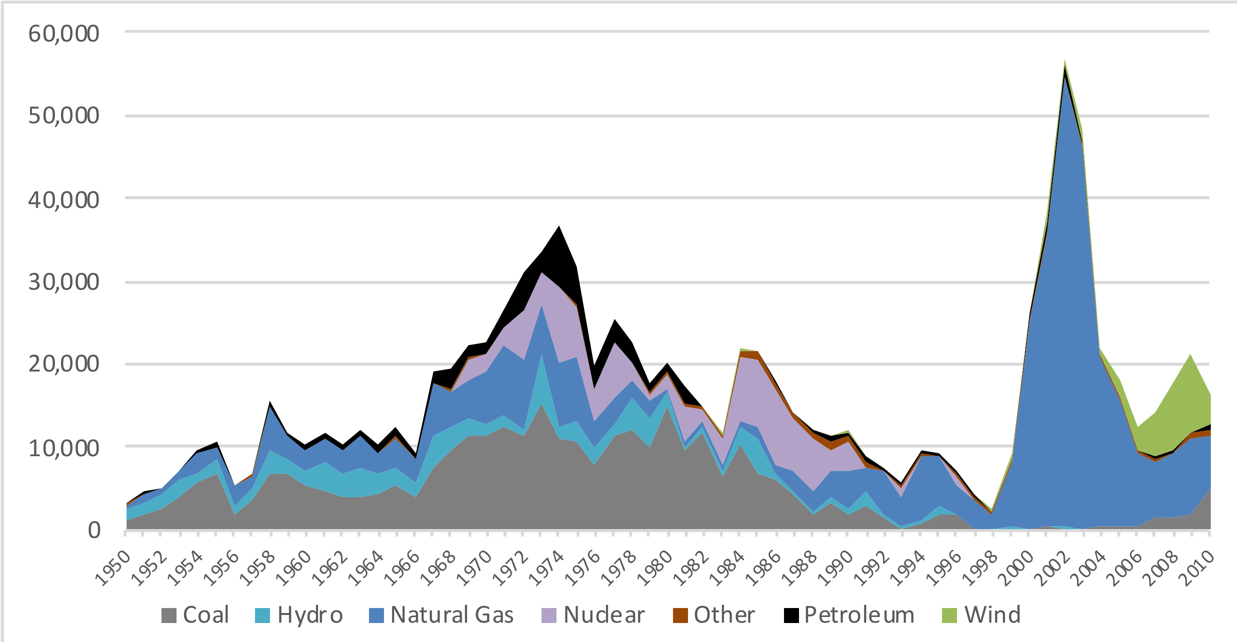
Source: Energy Information Administration (EIA)

Exhibit 5: U.S. Dispatchable Generation Capacity in GW, 2020-2040 (2020 Actual, Adjusted for Forecast Capacity Retirements in Later Years)[1]



1. Historical maximum non-coincident summer peak demand (789 GW, recorded in 2007 and 2012).
Source: Energy Information Administration (EIA)

Exhibit 6: Additions of Generating Capacity by Fuel, United States, 1950-2010 (MW)



Source: Energy Information Administration (EIA)

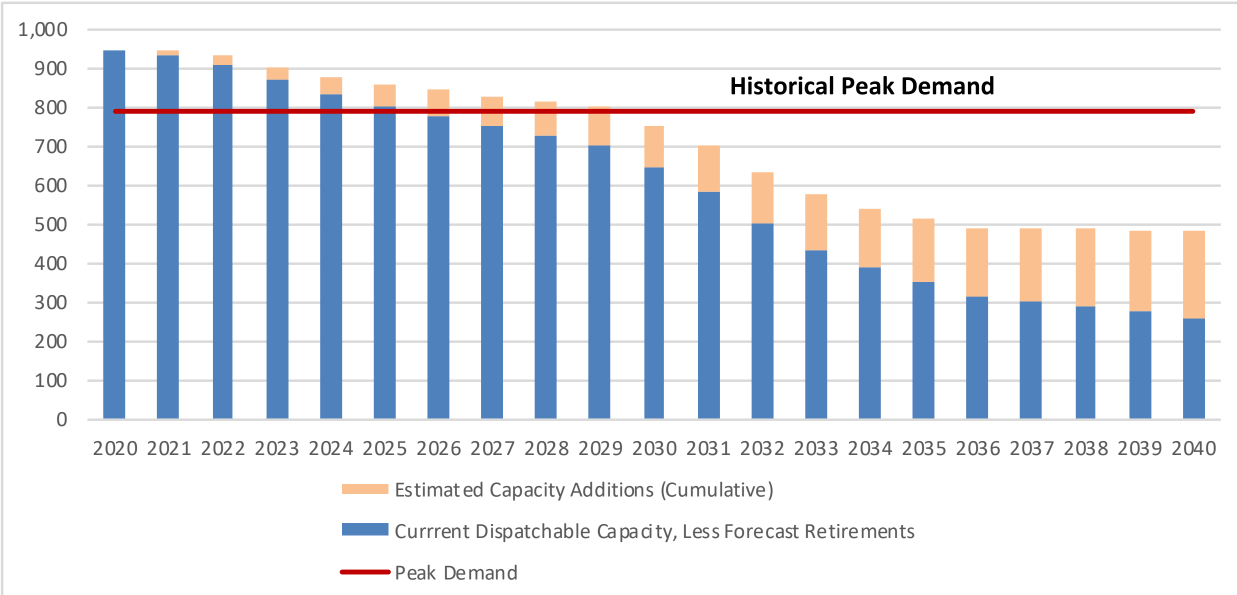
- **Historically, the average age at retirement of U.S. fossil fuel steam turbine generators has been 50 years. The bulk of these plants in operation today were commissioned between the late 1960s and early 1980s, and are thus likely to be retired over the next 10 to 15 years.**
  - The construction of oil-fired power plants in the U.S. was concentrated in the years from 1966 to 1982, with the peak in capacity additions occurring in 1974. (See **Exhibit 6**.). Assuming that those plants whose retirement has been announced are retired on schedule, and the remaining units are decommissioned after 50 years of service, we expect to see the 29 GW oil-fired generating fleet to be almost completely phased out in the current decade. (See **Exhibits 4** & **5**.)
  - The U.S. saw substantial additions of coal fired capacity over almost four decades, stretching from 1950 to 1990. (See **Exhibit 6**.) **Given the announced retirement dates of certain of these plants, and the expected useful lives of the remainder, we expect well over half of the country's 218 GW coal fired capacity today to be retired by 2030 and the fleet to be fully retired by 2040.** (See **Exhibits 4** & **5**.)
- **As can be seen in both Exhibits 1 and 5, we expect retirements of U.S. dispatchable generation capacity to accelerate markedly in 2030s, reflecting the advancing age of the country's 482 GW gas fired generating fleet.**
  - The U.S. has seen gas-fired capacity additions in virtually every year since 1950, but the nature of these power plants has changed over time.
  - Prior to 1980, natural gas was used to fire steam turbine generators similar to those used in coal and oil-fired power plants. Historically, the average age at retirement of these plants has been 50 years and we would therefore expect the remaining fleet of gas-fired steam turbine generators to be retired by 2030.
  - The last 15 years of the 20th century saw rising additions of simple cycle gas turbine power plants followed in the early years of this century by an unprecedented spike in gas fired capacity additions comprised of both simple cycle and combined cycle gas turbine plants. (See **Exhibit 6**.)

- Gas turbines, which operate at much higher temperatures than steam turbines, have an expected useful life of 25 to 30 years due to material fatigue, although life extension retrofits can extend this to 40 years through the refurbishment or replacement of damaged turbine blades. With many states and now the federal government seeking to decarbonize power generation over the years from 2035 to 2050, we have assumed that the country's simple and combined cycle gas turbine plants will be retired after 30 years of operation.
- The retirement of the remaining gas-fired steam turbine generators and the gas turbine capacity added from 1985 on will cause a material loss of gas fired capacity in the current decade, when we expect we expect over a quarter of the 482 GW gas-fired generating fleet currently in operation to be decommissioned. (See **Exhibits 4** & **5**.)
- Given the boom in U.S. gas-fired capacity additions from 1999 through 2006, we expect retirements of gas-fired generation capacity to accelerate markedly in the first half of the 2030s. We estimate that half of the gas-fired generating fleet currently in operation will be retired by 2032, two third by 2035 and three quarters by 2038. Thereafter, retirements are expected to slow, reflecting the more modest pace of capacity additions from 2007 on. (See **Exhibits 4** & **5**.)

- **The cumulative loss of U.S. oil, coal and gas-fired generation capacity will eliminate bulk of the 944 GW of dispatchable generating capacity currently in operation over the next 15 years.**
  - The cumulative impact of these capacity retirements, we calculate, will be to decommission ~300 GW or 32% of U.S. dispatchable generation capacity by 2030, ~600 GW or 63% of dispatchable capacity by 2035, and ~680 GW or 72% of dispatchable capacity by 2040. (See **Exhibits 1** & **5**.)
- **Even allowing for additions of new dispatchable generation capacity, the scale of the capacity erosion will be large enough to present a material threat to grid reliability.**
  - Over the five years 2015-2019, annual additions of dispatchable generation capacity in the United States averaged 11 GW.
  - If we assume that capacity additions continue at this pace, U.S. dispatchable generation capacity will not fall below the historical peak in summer demand of 789 GW until 2030.[2]
  - This shortfall will increase rapidly, however; from ~35 GW in 2030, we estimate it will rise to ~150 GW by 2032, ~250 GW by 2034 and ~300 GW by 2036. (See **Exhibit 7**.)
  - These shortfalls are equivalent to 5% of the historical peak in summer demand in 2030, 20% in 2032, 32% in 2034 and 38% in 2036. (See **Exhibit 8**.)

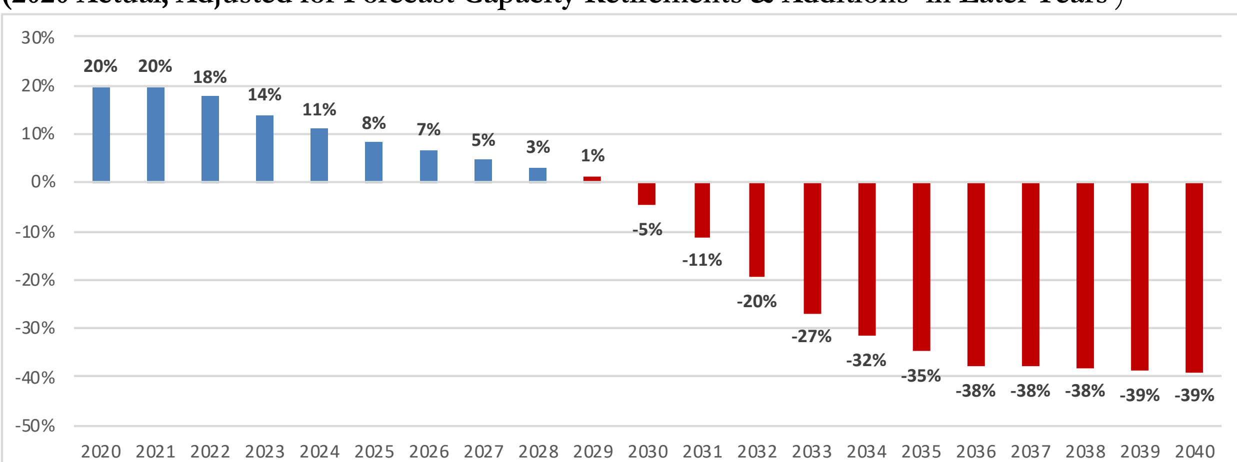
[2] U.S. non-coincident summer demand peaked at 789 GW in 2007 and again in 2012.

Exhibit 7: U.S. Dispatchable Generation Capacity in GW, 2020-2040
(2020 Actual, Adjusted for Forecast Capacity Retirements & Additions[1] in Later Years)



1. Annual capacity additions equal the average annual additions of dispatchable generation capacity in the United States over the five years 2015-2019. Historical maximum non-coincident summer peak demand equals 789 GW, recorded in 2007 and 2012.
Source: Energy Information Administration (EIA)

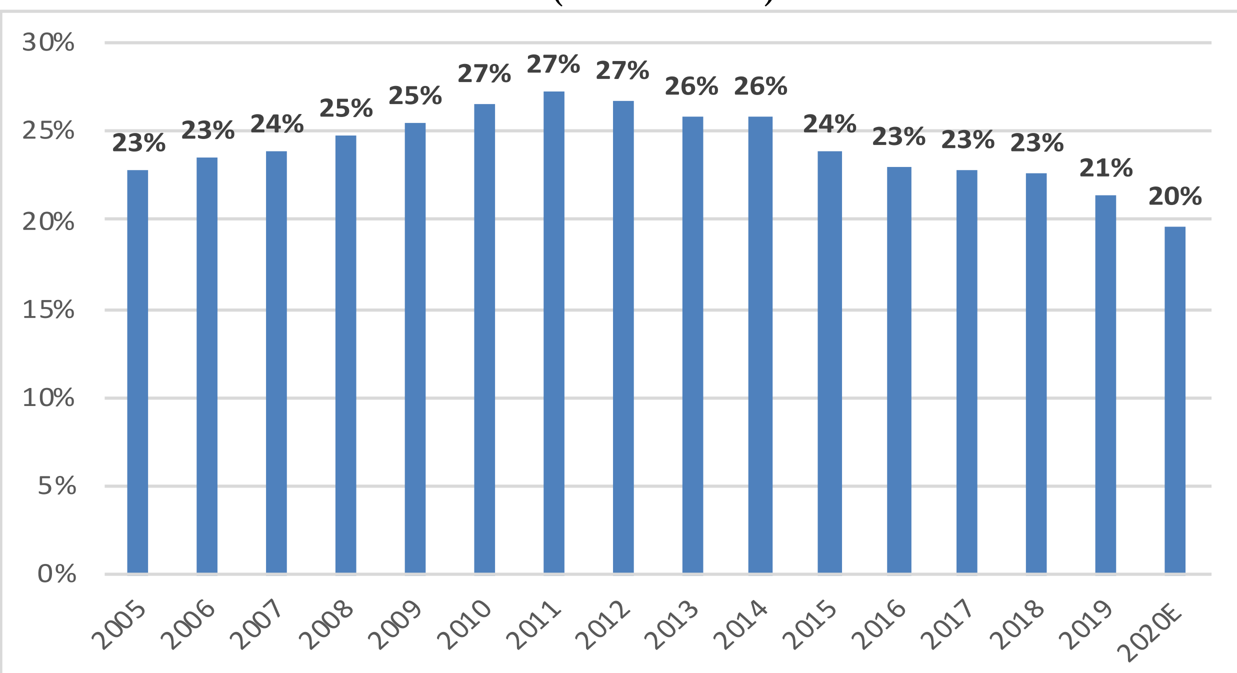
Exhibit 8: Excess/Deficit of U.S. Dispatchable Capacity Relative to Historical Peak Demand[1]
(2020 Actual, Adjusted for Forecast Capacity Retirements & Additions[2] in Later Years)



1. Maximum non-coincident summer peak demand equals 789 GW, recorded in 2007 and 2012.
2. Annual capacity additions equal the average annual additions of dispatchable generation capacity in the United States over the five years 2015-2019.
Source: Energy Information Administration (EIA)

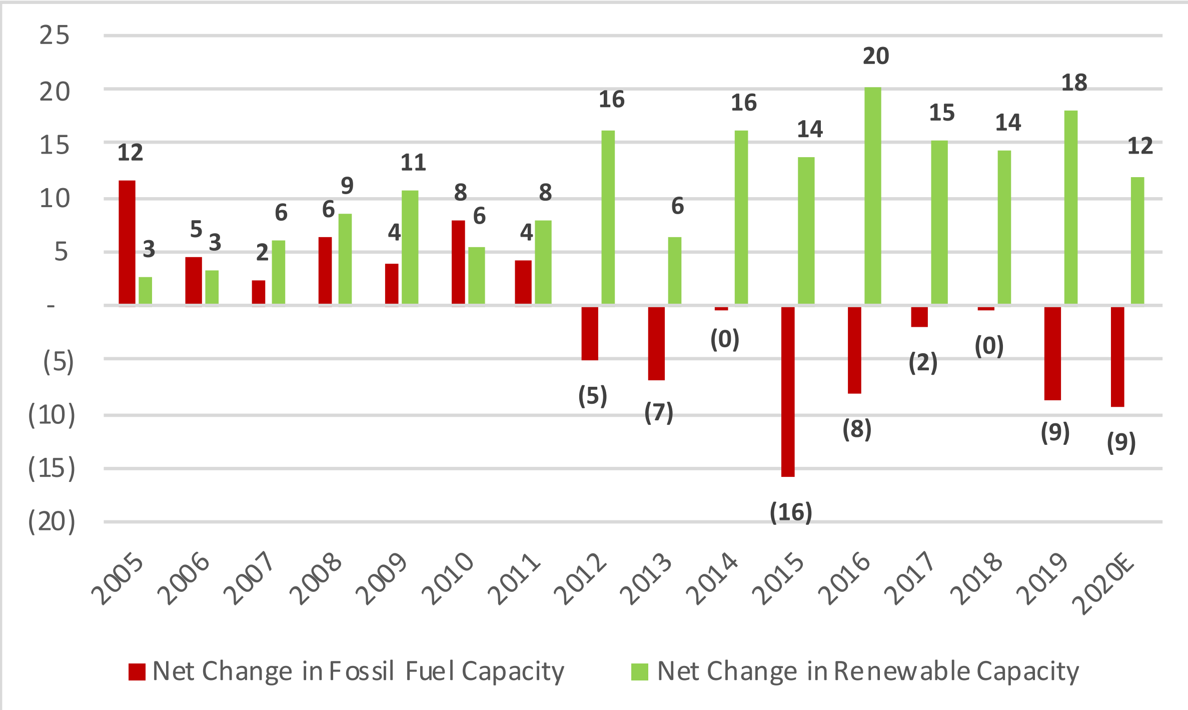
- The forward-looking analysis presented above suggests that the rapid erosion of U.S. dispatchable generation capacity expected over the next 15 years stems from a fortuitous coincidence: the near-simultaneous peak in retirements of two generations of power plant, fossil fuel steam turbines and simple and combined cycle gas turbines.
- **It is important to emphasize, therefore, that the erosion of U.S. dispatchable generation capacity relative to the historical peak in summer power demand has been ongoing for the last decade.**
  - As illustrated in **Exhibit 9**, the excess of dispatchable generation capacity relative to the historical peak in summer power demand reached its highest point in 2011 and has been declining steadily since.
  - This in turn reflects nine consecutive years of net decreases in fossil fuel generation capacity as capacity additions have failed to keep up with historical retirements. (See **Exhibit 10**).
  - This decade of under-investment in dispatchable generation capacity has coincided with a historic expansion in U.S. renewable generation capacity. (See **Exhibit 11**.)
  - From 2010 through 2020, non-hydroelectric renewable generation capacity in the United States expanded by ~140 GW, more than the combined capacity of the nation's hydroelectric and pumped storage power plants.
  - Over the same period, the U.S. fossil fuel fleet contracted by over 50 GW.

Exhibit 9: Excess of Dispatchable Capacity in Service Over Maximum Non-Coincident Peak Summer Demand (2007 = 789 GW)



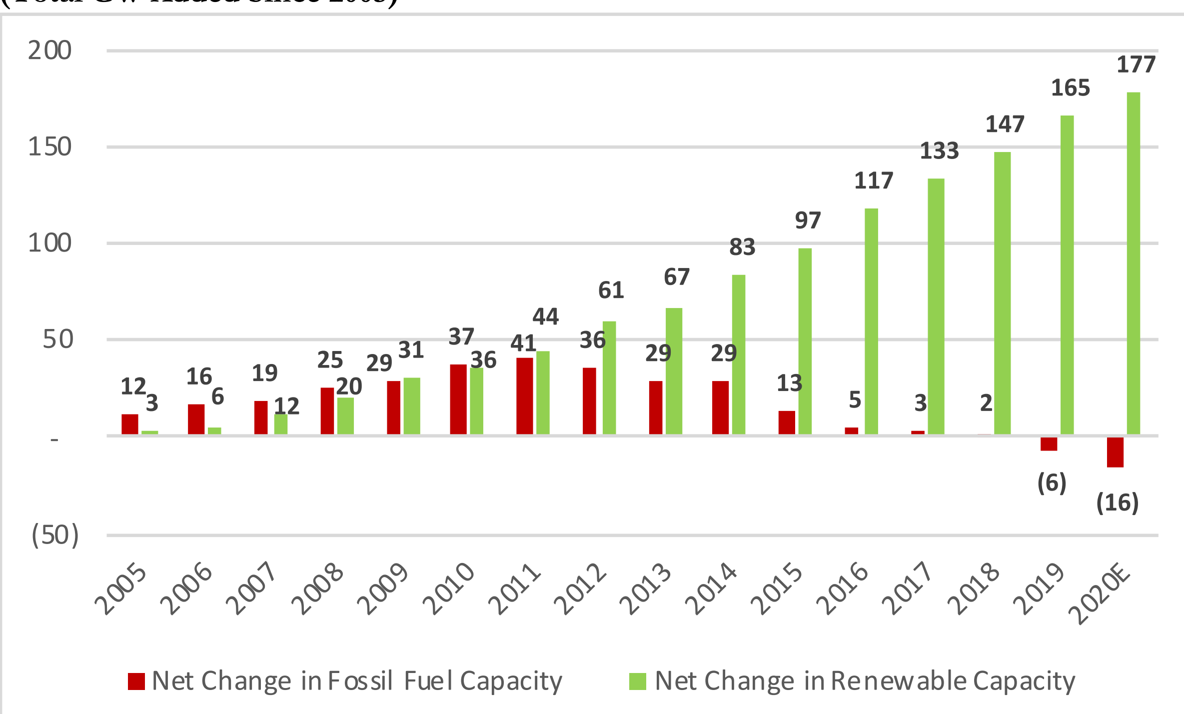
Source: Energy Information Administration (EIA)

Exhibit 10: Net Change in Renewable and Fossil Fuel Generation Capacity (GW Added per Year)



Source: Energy Information Administration (EIA)

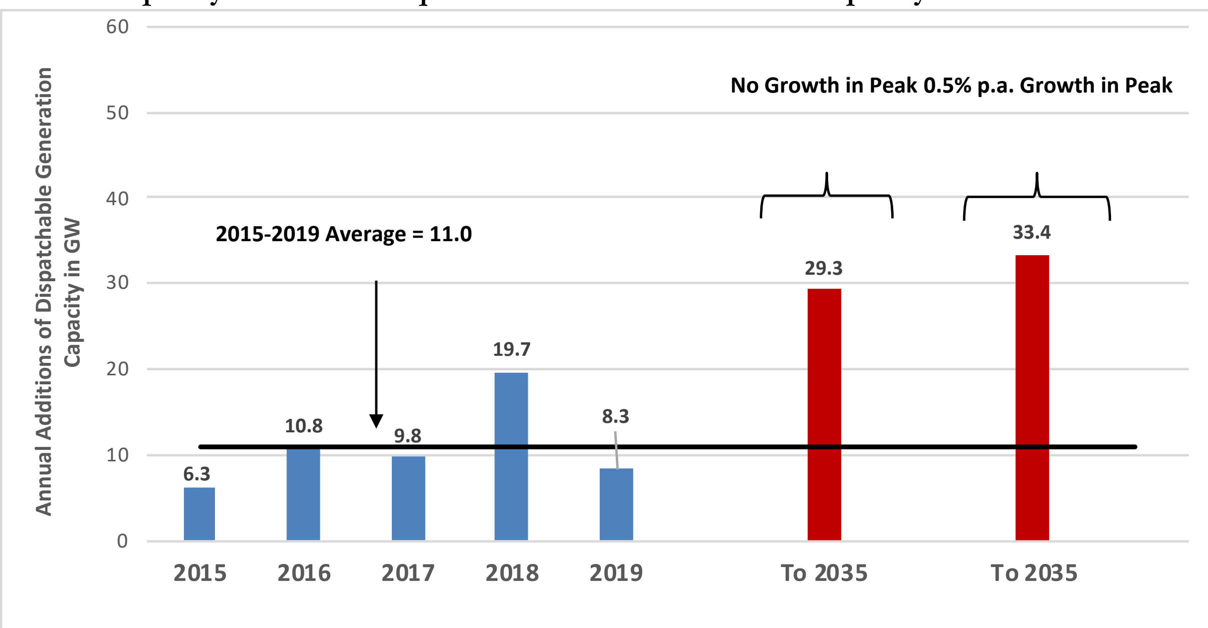
Exhibit 11: Net Change in Renewable and Fossil Fuel Generation Capacity (Total GW Added Since 2005)



Source: Energy Information Administration (EIA)

- **If the U.S. is to halt this erosion of its dispatchable generation capacity, and ensure that in future such capacity is maintained at a level at least equal to the historical peak in summer demand, the pace of investment in new dispatchable generation must accelerate markedly or significant investment made to extend the life of existing capacity.**
    - **Exhibit 12 presents the historical additions of dispatchable generation capacity over the five pre-pandemic years 2015-2019. The average pace of capacity additions over this period was 11 GW annually.**
    - **However, as can be seen there, if dispatchable generation capacity is to remain at least equal to the historical peak in summer demand, additions of such capacity must increase to 29 GW annually through 2035.**

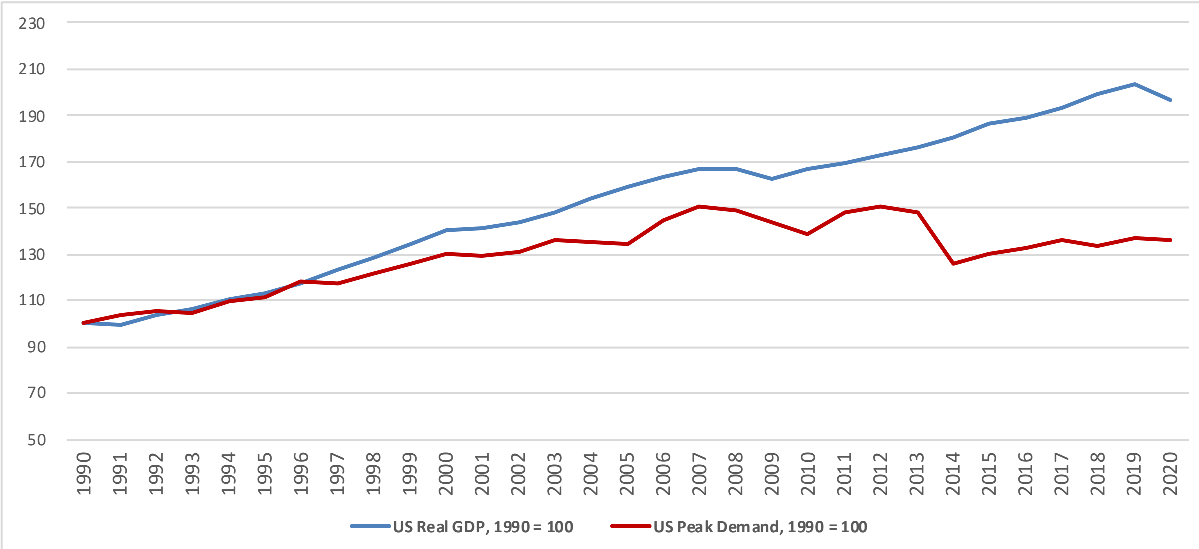
Exhibit 12: U.S. Historical Additions of Dispatchable Generation Capacity vs. Annual Capacity Additions Required to Meet Forecast 2035 Capacity Shortfall



Source: Energy Information Administration (EIA)

- Over the last four years, the non-coincident peak in summer power demand has remained at a level comparable to that of 2003. (See **Exhibit 13**.). **The failure of peak power demand to grow has ameliorated the reliability impact of the erosion of U.S. dispatchable generation capacity.**
    - **Were growth in peak power demand to resume, even if only at 0.5% p.a., the additions of dispatchable generation capacity required through 2035 would increase to 34 GW annually, or three times the average level of the five pre-pandemic years.**

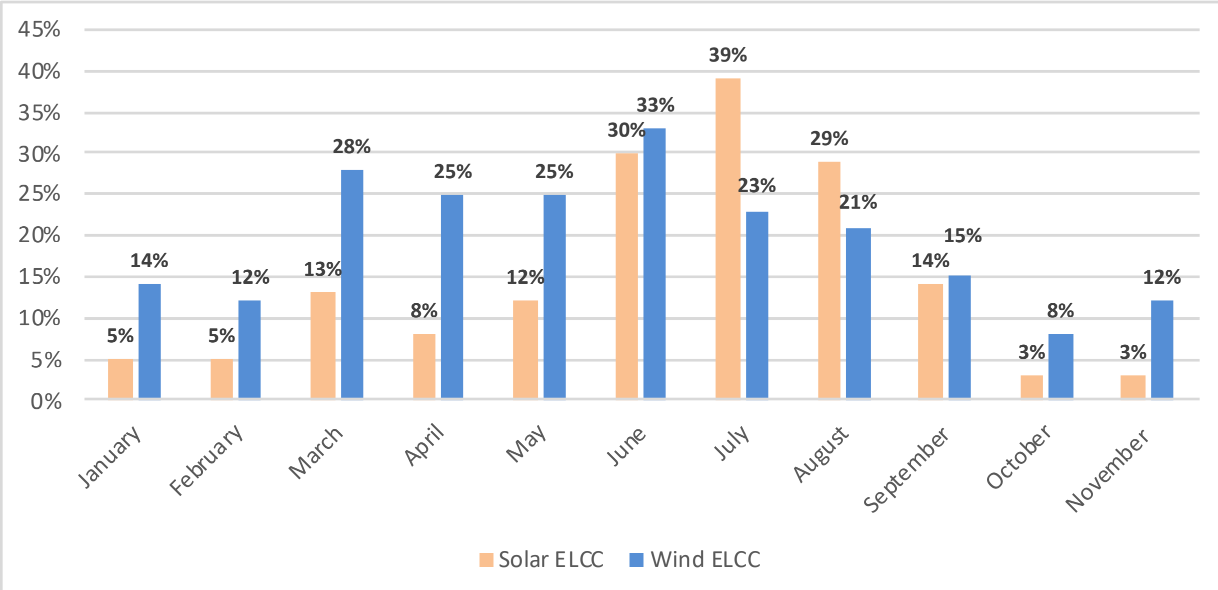
Exhibit 13: Comparison of the Growth in U.S. Peak Power Demand[1] to the Growth in U.S. Real GDP (1990 = 100)



1. Historical maximum non-coincident summer peak demand (789 GW, recorded in 2007 and 2012).
Source: Energy Information Administration (EIA), Bureau of Economic Analysis (BEA)

- **Intermittent renewable resources, even when combined with grid scale energy storage, can only offset to a limited degree the loss of firm capacity expected over the next two decades.**
  - The energy output of the lost capacity can be substituted by renewables; however, the load serving capability of the lost resources – their ability to provide power as required to meet demand – can be replaced with a combination of intermittent wind, solar and storage only at prohibitive cost.
- **Utility regulators and regional transmission operators assign very low capacity values to intermittent renewable resources.**
  - To estimate the capacity value of renewable resources, regulators and system operators calculate the Effective Load Carrying Capability (ELCC) of wind, solar and other renewables. ELCC is the amount of incremental load, or power demand, that a resource can dependably and reliably serve. It is expressed as a percentage of nameplate capacity, or the manufacturer's estimate of the maximum instantaneous output of a wind turbine, solar panel or other generating unit.
  - California is a state that has both high quality renewable resources and a strong political commitment to substitute renewable energy for fossil fuel generation. The California Public Utility Commission (CPUC) conducts an annual resource adequacy proceeding to assess the adequacy of the generation resources available to the state's utilities to meet system demand. In connection with the 2020 proceeding, the staff of the CPUC estimated the monthly ELCC of the state's wind and solar resources. The results of this analysis are presented in **Exhibit 14** below:

Exhibit 14: Effective Load Carrying Capability of New Wind and Solar Resources in California



Source: California Public Utilities Commission, Energy Division, Energy Resource Modeling Team, February 2019.

- As can be seen in **Exhibit 14**, the monthly ELCC of solar in California ranges from a high of 39% of nameplate capacity in July to a low of 1% in December. In July, days are long, the sun is high in the sky, and California's skies are generally clear; in December, days are at their shortest, the sun is low in the sky, the skies cloudy, and the weather can be rainy for days on end.
- The ELCC of wind avoids the seasonal lows of solar but still shows wide variability across the year. From 33% in June, the ELCC of wind drops to 8% in October.
- The marked seasonal and diurnal pattern to the output of wind and solar capacity limits the ability of capacity additions to increase load serving capability. Adding solar capacity cannot increase solar generation at night, and adding wind capacity will not materially enhance its ability to serve load in months, like October in California, when wind rarely blows.

- **Even when backstopped by grid scale energy storage, the capacity value of intermittent renewable generation can fall far short of system needs.**
  - The grid-scale energy storage systems available today, which generally deploy lithium ion batteries, may be discharged at capacity for a maximum of four hours (duration of discharge).
  - Batteries may thus be used to bridge gaps between prevailing power demand and the system's total renewable output, but only for intervals of four hours or less. To bridge gaps of eight hours duration, twice as much storage capacity must be deployed, for 12 hours, three times.
  - Even at high levels of renewable penetration (>80%), models comparing California's hourly power demand with the hourly availability of its renewable resources have shown that the output of the system's renewable resources can fall short of prevailing demand for 12 hours a day. These gaps tend to occur when the generation of California's wind and solar fleets is at its seasonal low (October through January). In addition to being of long duration, these shortfalls can be deep (characterized by available renewable generation falling short of prevailing demand by 50% or more) and recurrent (repeating for several days during a week of bad weather.)
  - Bridging deficits such as these can require energy storage capable of supplying 50% of system load for 8 to 12 hours a day. The four-hour duration of discharge typical of lithium ion batteries today implies that two or three sets batteries, each capable of serving 50% of system load for four hours, must thus be fully charged and available each day.

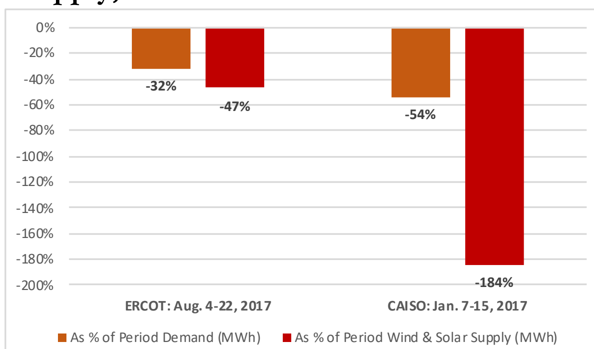
- At the end of the day, moreover, these batteries must be recharged. If these batteries are to be available for the following day's use, the system's renewable resources must be adequate to meet not only the hourly demand for power but also the charging load of the batteries. This implies a need for renewable resources capable of generating 150% of system load for 8 to 12 hours -- during those months of the year when the availability of wind and solar energy is at its lowest.

- We provide examples of such conditions in our research report of June 18, 2019, *The Cost to Achieve 100% Renewable Energy: A Comparative Analysis of Texas and California*, in which we compared hourly power demand in California and Texas in 2017 against the predicted output of renewable fleets capable of supplying 80% of the electric energy needs of these two states.
  - Even assuming the continued availability of CAISO's substantial hydroelectric and geothermal resources, and additional wind and solar resources capable of ensuring 80% renewable penetration, CAISO's total renewable generation would have fallen short of system demand over a period of eight days in January 2017. The cumulative energy deficit over this eight day period is equivalent to 54% CAISO's total electricity demand. Hourly deficits in renewable generation reached levels of up to 16 GW, or 75% of prevailing demand. In the absence of CAISO's existing fossil fuel capacity, such a shortfall would have precipitated blackouts across the state.

Exhibit 15: Largest MWh Shortfalls in the Supply of Renewable Generation Relative to Then Prevailing System Demand and Wind and Solar Supply, ERCOT & CAISO 2017

Largest Cumulative Shortfall of Renewable Generation vs. Demand

	Dates	Millions of MWh	As % of Period Demand (MWh)	As % of Period Wind & Solar Supply (MWh)	As % of Total Annual Demand (MWh)
ERCOT	Aug. 4-22	(7.3)	-32%	-47%	-2.0%
CAISO	Jan. 7-15	(2.5)	-54%	-184%	-1.1%



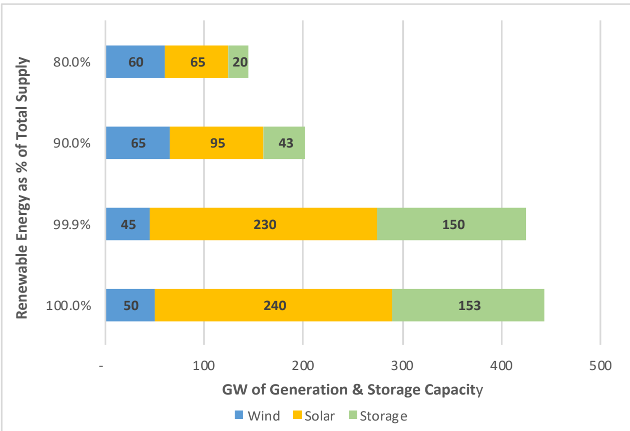
Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

- **Bridging gaps of this scale and duration by adding additional renewable resources during those months of the year when the availability of wind and solar energy is at its lowest, complemented by batteries capable only of four hours discharge, is inherently inefficient, requires enormous resources and adds massively to total cost of energy supply.**
  - To estimate the all-in cost of high levels of renewable generation, our 2019 analysis assumed that CAISO and ERCOT maintained access to their large existing gas fired generation fleets as well as their existing hydroelectric and geothermal resources.
  - The dispatchable capacity that these resources offer significantly reduces the cost of achieving 80% and 90% levels of renewable penetration, as the conventional power plants can backstop the supply of energy to the grid during hours of low wind and solar generation.
  - By contrast, transitioning to an all-renewable energy system (100% renewable penetration), requires the addition of sufficient renewable generation and storage capacity to meet demand during every hour of the year.
  - **Exhibit 16** presents our estimates of the lowest cost combination of new wind and solar resources, plus grid scale energy storage, required to achieve 80%, 90%, 99.9% and 100% renewable penetration.
  - **Exhibit 17** estimates the aggregate capital cost of these new wind, solar and energy storage resources based upon *Lazard's Levelized Cost of Energy Analysis – Version 12.0* and *Lazard's Levelized Cost of Storage Analysis – Version 4.0*.

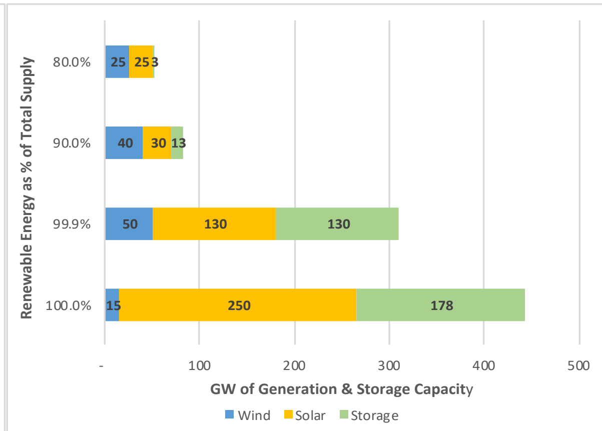
- Finally, in **Exhibit 18**, we calculate the levelized cost of energy resulting from the deployment of these resources and quantify its impact on the system wide cost of supplying full requirements power to the California and Texas grids. As can be seen there, we calculate that achieving 100% renewable penetration would raise the all-in cost of full requirements power to 3x the level prevailing in 2018 in Texas and 4x the level prevailing in 2018 in California.

Exhibit 16: Lowest Cost Combination of Wind, Solar & Storage Resources at Different Levels of Renewable Penetration (GW)

ERCOT



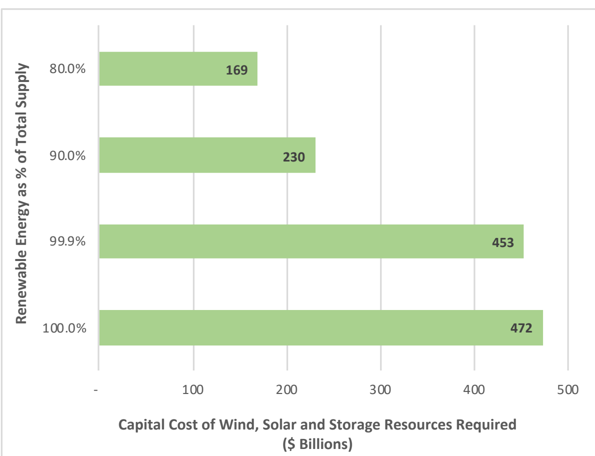
CAISO



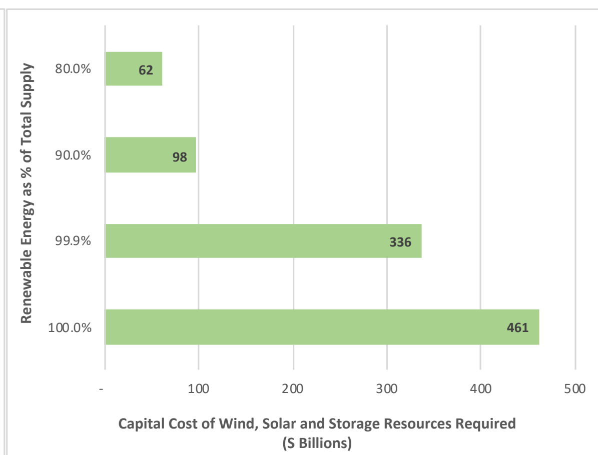
Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

Exhibit 17: Capital Cost to Achieve Various Levels of Renewable Penetration ($ Billions)

ERCOT

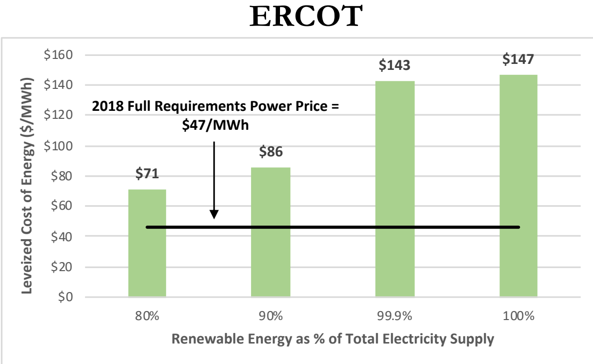


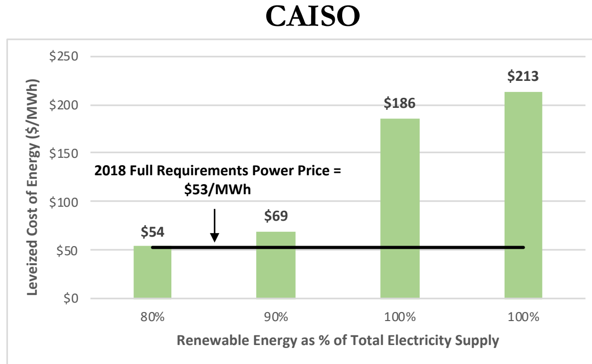
CAISO



Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

Exhibit 18: System Levelized Cost of Energy at Various Levels of Renewable Penetration





Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

- In an analysis entirely independent of our own, the California Energy Commission reached a very similar conclusion:

  > *Achieving 100% zero-carbon generation appears to be cost prohibitive without major advances in low-cost energy storage. In the High Electrification scenario, natural gas generation provides the remaining 5% of energy requirements and helps ensure resource adequacy and energy sufficiency during periods of low renewable generation. This 5% of natural gas generation helps to contain the cost impacts of the scenario compared to a 100% zero-carbon scenario.*
  >
  > California Energy Commission, *Deep Decarbonization in a High Renewables Future: Updated Results from the California PATHWAYS Model* , June 2018.

- The Princeton University study, *Net Zero America: Potential Pathways, Infrastructure and Impacts,* which analyzes alternative pathways for the United States to achieve net zero emissions by 2050, reaches a similar finding.
  - Commenting on the outcomes of five alternative scenarios for achieving net zero emissions by 2050, the authors note: "Installed capacity of 'firm' generation sources — technologies that can produce power on demand, any time of year, for as long as required — remains similar to current levels in all scenarios." [3]
- If this assessment is accurate, the impending loss of 63% of the country's dispatchable generation *capacity* by 2035 is an issue that must be addressed with the same urgency as the transition to renewable sources of *energy*.
  - Failure to do so, and the consequent loss of system reliability, will interrupt and potentially derail the transition from fossil fuels to renewable energy in the power sector, as well as the electrification of energy use in transportation, industry and commercial and residential buildings that could enable their transition from fossil fuels.
- The scale and immediacy of the capacity challenge, moreover, should spur serious consideration of alternative strategies to ensure system reliability.
  - In particular, options to preserve or replace existing dispatchable capacity -- such as carbon capture and sequestration, the firing of existing gas turbine generators with green hydrogen or green methane, modular nuclear reactors, and long duration energy storage technologies such as pumped storage -- should be assessed against the extremely high marginal cost of continuing to deploy intermittent renewable resources backstopped by short duration batteries.

[3] E. Larson, C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R. Socolow, EJ Baik, R. Birdsey, R. Duke, R. Jones, B. Haley, E. Leslie, K. Paustian, and A. Swan, *Net-Zero America: Potential Pathways, Infrastructure, and Impacts*, Princeton University, Princeton, NJ, December 15, 2020.

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- Retrofitting dispatchable generation resources may enable the bulk power system to capitalize on the installed capacity of existing gas turbine power plants and their gas supply infrastructure. Alternatives include:
  - Upgrading existing simple and combined cycle gas turbine power plants with carbon capture and sequestration technology, possibly in combination with retrofits or replacements of existing gas turbines to extend the useful lives of these plants; and
  - Modifying existing gas turbines to burn green methane, manufactured by combining hydrogen, produced through the electrolysis of water using renewable electricity, with carbon dioxide captured from the combustion of fossil fuels in power generation or industrial processes.

- Equally important will be the creation of economic incentives to deploy these low-emitting replacements for the nation's fossil fuel generation capacity and maintain large portions of the existing fleet until they can be replaced or retrofitted with these alternatives.
  - Regulated utilities will have to work with their regulators to identify, design and deploy the lowest cost options to maintain system reliability while still achieving emissions reduction targets.
  - Regional transmission organizations operating competitive markets for energy and capacity must redesign these markets to create incentives for a wider range of power generation and CO_2 abatement technologies. Importantly, these technologies will often involve larger capital outlays per megawatt, significantly higher technological risk, and longer construction periods than are typical of the gas turbine capacity additions these markets target today.